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Compaction of palm kernel shell biochars for application as solid fuel

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ABSTRACT

Palm oil is the most widely sold oil across the globe. The production of palm oil results in vast amounts of biomass waste. The palm kernel shells (PKS) can be used for energy production through gasification or combined heat and power (CHP). After gasification, some PKS remains as charred residue. In this manuscript, briquettes/pellets are produced from these biochars. The palm kernel shell biochars (PKSB) show very high calorific value exceeding typical values for biomass. The effects of water content, compaction pressure, feed particle size, compaction retention time, and the use of starch as a binder have been studied. The tensile crushing strength, impact resistance, and water resistance (immersion tests) show that the starch binder is imperative for suitable briquette quality. The use of starch increases the tensile crushing strength from less than 40 kN m^{-2} to more than 800 kN m^{-2} in the weakest (longitudinal) orientation. The tensile crushing strength of the starch-bound briquettes increases as their water content evaporates during storage and curing. It is speculated that the evaporation of water from the starch-bound sample allows for better cementing of the starch and PKSB particles.

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1. Introduction

In recent years, due to the dwindling reserves of fossil fuels on one hand and the many benefits associated with biofuels on the other, utilizing biomass as a source of energy is on the rise. Densification of biomass into briquettes, pellets, cubes etc. is a method employed for increasing the intrinsic density of materials from 40 to 200 kg m^{-3} to 600–800 kg m^{-3} for more favourable employment [1]. Because of the uniform shape and size of densified products, they can more easily be handled and used in standard combustion equipment. There are various books and review articles which have favourably compiled information regarding biomass densification [1–3].

On the other hand, the most widely traded edible oil around the globe is palm oil. The production of palm oil has more than doubled in the past two decades. In obtaining edible oils from palms, a large amount of residue is produced.

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Nomenclature

Roman

D	diameter of sample [m]
F	maximum force applied to break sample in tensile strength test [N]
h	height of sample [m]
n_d	number of drops in impact resistance testing
n_p	number of pieces of broken sample in impact resistance testing

Greek

ε	porosity
ρ_a	apparent density [kg/m^3]
ρ_t	true density [kg/m^3]
σ	tensile crushing strength [N/m^2]

Abbreviations

CHNS	carbon hydrogen nitrogen sulphur
CHP	combined heat and power
HHV	higher heating value [J/kg]
IRI	impact resistance index
LHV	lower heating value [J/kg]
PKS	palm kernel shell(s)
PKSB	palm kernel shell biochar(s)
XRF	X-ray fluorescence

One such residue is the palm kernel shell (PKS). PKS is reported to have a high calorific value allowing it to be used as fuel in cogeneration plants to generate both heat and electrical power. The heating value of the shell has been reported as 17.4 MJ kg^{-1} [4] with a higher heating value of 23.0 MJ kg^{-1} [5]. Calculations show that the shell and the fibre residue alone from palm oil production can provide more than enough steam and electricity for the entire palm oil mill [6].

1.1. *Thermal pretreatment of PKS*

There are some disadvantages when using solid biomass such as PKS as fuels, namely their low energy density, low heating value, high moisture content, low carbon content, high oxygen/carbon ratio and hygroscopic nature, as well as soot formation, transportation difficulties and poor grindability [7]. In order to overcome these drawbacks, pretreatment processes are often necessary. The products of biomass thermal treatment can be divided into solid residues with high-density energy, referred to as ‘biocoal’ or ‘biochar’, and a volatile fraction. The volatile fraction can in turn be divided into condensable liquids (such as water, acetic acid, and tars) and non-condensable gases. The solid product of a thermal treatment process is dry and has no unfavourable biological activity such as biodegradation, allowing for long storage durations. The heat-treated solid is much more brittle than the original biomass, improving the grindability of the fuel [7–9].

Prior to thermal treatment, the materials are usually first refined, meaning that the unwanted fractions are physically removed. This is followed by a preheating step to dry the material. After the products are heat-treated they are usually cooled to avoid fire hazards. Densification in the form of pellets or briquettes is carried out to further increase the energy density of the solid fuel [10]. PKS have been heat-treated in several studies aiming at producing more satisfactory solid fuels. In one study, PKS was treated at temperatures ranging from 513 to 553 K for durations ranging from 1800 to 5400 s (30–90 min) [11]. The carbon content of the PKS increased at the expense of hydrogen and oxygen resulting in an increase of 5–16% in heating value. In another study, the oxygen/carbon ratio, hydrogen, and oxygen mass fractions were shown to decrease and the calorific value was shown to increase from 18.9 MJ kg^{-1} (raw) to 22.8 MJ kg^{-1} (after treatment at 573 K) [9]. A mass loss of 45–55% was observed for different conditions. The type and amount of gas released during the process is a function of the type of biowaste, temperature, and treatment duration. Different types of thermal treatment can be applied to PKS [12], such as torrefaction, mild thermal treatment in the presence of steam [13], and extreme pyrolysis at higher temperatures [14]. The production of hydrogen gas at elevated gasification temperatures is also an area of research [15–17].

1.2. *Background to PKS densification*

A number of densification studies regarding PKS have been reported [18,19]. It has been estimated that the production of durable pellets from palm kernel residues will cost less than £50 per 1000 kg [20,21]. Since PKS is composed of more than 50% lignin [22], densification may be aided by the high lignin content acting as a natural binder. Some authors have suggested that heating the biomass during compaction will be beneficial for the durability of the final product [23,24]. The positive effect of heating has been attributed to the glass transition temperature of lignin. Nasrin et al. [25] densified oil-palm biomass at operational temperatures of 423–523 K and pressures of 7 MPa without the use of binders. Under these conditions, the lignin content within the biomass was softened and resulted in particle bonding. Nonetheless, the study concluded that the addition of binders could be beneficial for the final quality of the briquettes. Once ignited, the briquettes generated about 130 W of thermal output [25].

To date, more than 50 organic and inorganic binders have been tested for densification [26]. In the case of starch, first, the water-starch solution is usually heated to sub-boiling temperatures until the mixture becomes sticky and gelatinous. The solid biomass is then mixed and coated with the binder before being densified. One study using a mixture of shells and fibres employed 10% starch and 50% hot water to enhance the densification process [27]. The compaction pressure was in the range of 5–13.5 MPa and the briquettes exhibited an average strength of 2.56 kN m^{-2} [27]. Glycerin has also been used as a binder for mixed palm biomass briquettes. The optimum mass ratio of raw material, water, and waste glycerol was found to be 50:10:40 [28]. Sing and Shiraz Aris [29] dried, pulverized, and sieved PKS and palm fibres to smaller than 50 μm before densification with the aid of paper and starch binders. In a study by Arzola et al. [30], raw PKS was densified using molasses at 15%, 20% and 25% as an added binder. As far as the durability was concerned, the binder content had great influence, yielding more durable pellets as more binder was employed. Palm oil was also tested as a binder, but since the results were poorer than those obtained using molasses, they were not reported.

Starch is an ordered, densely-packed, semi-crystalline polymer of α-D-glucose existing in the form of granules. Starch is widely present as a carbohydrate reserve in plants and can be found in the leaves, stems, roots, and fruits. Although starch is hydrophilic due to its large number of hydroxyl groups, in its raw form, it remains insoluble in water at room temperature. Starch consists of a mixture of polysaccharides, predominantly amylose (linear) and amylopectin (branched). As starch is heated in water, its intermolecular bonds weaken leading to rapid and irreversible swelling and water uptake. As swelling proceeds, starch molecules (in particular amylose) leach into the solution [31]. Gradually, the semi-crystalline structure is eliminated and a viscous solution is formed. The solution viscosity is dependent on the starch source and concentration. This heat-induced breakdown in water is known as gelatinization. In other words, gelatinization is described as a transition of starch from an *ordered* to a *disordered* state [32]. In the gelatinization step, dispersed starch molecules in the aqueous medium re-associate and form three-dimensional gel network structures which act as a binder [31].

The significance of the current research compared to the previously published studies on PKS densification is that the majority of them have used raw PKS, whereas here we are using gasified PKS as the feed. The authors are aware of only one other study by Ugwu and Agbo which employs thermal pretreatment in the form of pyrolysis prior to densification of PKS [33]. In that study, the PKS were first carbonized in a simple container with the help of kerosene to facilitate ignition. The container was covered for 8 h to prevent entry of air. The biochar was subsequently pulverized and screened through a 250 μm sieve. The binder was prepared as follows: cassava root was peeled, washed, dried, pulverized and dissolved in 100 cm^3 of cold water. In another container, 400 cm^3 of water was boiled. The cold water (containing the cassava) was added to the boiling water and mixed until starch gel started to emerge. While the starch gel was still warm, 750 g of pulverized PKS biochar was added and mixed until a thick, black mixture formed. Two types of briquettes were produced: the first type by pressing the mixture into a cylindrical mould; the second type by manual moulding with hands. The study targeted briquette production by the rural populace with no access to costly equipment. The briquettes showed calorific values of 23.6 MJ kg^{-1}. Although pelletising PKS biochar is rarely studied, the pelletisation of charcoals from other biomass such as loblolly pine [34], switchgrass [35], sawdust [36] and even beehives [37] has been extensively documented.

2. Materials and methods

2.1. *Feedstock and binders*

In the current study, PKS from a plantation in Indonesia were fed as fuel to a gasifier by a Hong Kong based company. The gasification occurs in a bubbling bed reactor at approximately 1000 K for less than 10 s producing high calorific value syngas from the PKS. The emerging gases from the gasifier are then used by the company for generating electricity with a turbine. However, after the gasification and extraction of gases is complete, a solid residue known as palm kernel shell biochars (PKSB) remains. These residues are currently expunged from the gasifier and discarded by the company. This manuscript is concerned with the further utilization of the PKSB residues by compacting them into solid fuel briquettes.

The as-received PKSB consisted of black solid pieces with sizes that range from microns to the order of millimetres. Water and/or soluble starch were used as binders. The soluble starch (BDH Laboratory Supplies, UK, fine white powder) was first dissolved and gelatinized in water at 363.16 K before being mixed with the PKSB. When the starch binder was employed, the PKSB:water:starch weight ratio was fixed at 70:20:10. In order to examine the effect of particle size on the PKSB briquettes, the as-received PKSB were crushed using a strain frame to powders followed by sieving. Three mesh sizes were used, 3000 μm, 700 μm, and 300 μm.

2.2. *Characterization*

The quantitative composition of the samples was determined by X-ray fluorescence (XRF) spectroscopy (Philips PW 1480 spectrometer). Elemental CHNS analysis was performed for determination of the absolute amounts of the constituent elements using a Perkin–Elmer 2400 elemental analyzer, with a precision of 100 ng. The ash content of the samples were determined by combusting samples in the presence of air at 1173 K using a thermogravimetric analyzer. All values reported in this paper are dry basis unless otherwise stated.

The dimensions of each briquette were measured with digital calipers, and the porosity, ε, of each sample was determined as follows:

$$\varepsilon = 1 - \frac{\rho_a}{\rho_t} \quad (1)$$

where ρ_a is the apparent density, and ρ_t is the true density of the sample. The true density of each sample was measured using helium pycnometry (Micrometrics, USA). The apparent density (also known as the intrinsic density) of each sample is calculated by dividing its mass (as measured with a benchtop scale) by its volume (calculated from the dimensions measured with the calipers). Bulk density measurements have not been carried out.

2.3. *Compaction*

A modified 50 kN fully instrumented strain frame (Zwick/Roell, Germany) fitted with a load cell and displacement transducer with resolutions of ±0.1 N and ±1 μm, respectively, was employed for compaction experiments [38]. In each run, the total weight of the sample (including water and/or starch) was 6 g. The PKSB was poured into a stainless steel (316 SS) compaction cell of diameter 25 mm. A stainless steel (316 SS) cylindrical ram fitted with a high density polyethylene tip (diameter 24.9 mm) was used to compact the samples at a steady ram velocity of 0.5 mm s^{-1} to the desired final applied pressure. The sample was held at the final pressure for a specified duration, after which the ram was withdrawn. The height of a typical densified sample after ejection was 10–14 mm.

2.4. *Quality testing*

Forces that can cause damage to a densified briquette or pellet can be classified as compression, impact, and shear. The compressive forces are those that lead to crushing; impact forces are those that would cause a briquette/pellet to shatter; and shearing forces are those that lead to abrasion on the edges and surfaces. Binding forces within densified products can be classified as solid bridges, attraction forces between constituent solid particles, mechanical interlocking bonds, adhesion, cohesion, interfacial forces and capillary pressure [1]. In a comprehensive study, Richards has recommended 375 kN m^{-2}, 50, and 95% as the target levels for crushing strength, impact resistance index (IRI), and water resistance, respectively [39]. In the present manuscript, the guidelines proposed by Richards have been used as the benchmark for characterizing the compacted PKSB product. Here, a brief explanation for each quality test is given. Experiments were performed in triplicate and range bars are used to show the maximum and minimum values.

2.4.1. *Compressive and tensile strength*

The quality of a densified cylindrical product is often measured through crushing. The crushing can either be done parallel or perpendicular to the cylindrical axis, as shown in Fig. 1.

In general, the sample strength is higher in the cylindrical axis direction, referred to as the compressive strength (Fig. 1a). The strength of the sample perpendicular to the cylindrical axis is known as the tensile strength (Fig. 1b) [1]. In this manuscript, the sample strength was determined by performing tensile strength tests in which a diametrical force was applied to the densified product as in Fig. 1b. The sample was placed on its side on a stainless steel base platen, with a 40 mm diameter stainless steel platen above it. The top platen was lowered with a speed of 0.5 mm s^{-1} until it came into contact with the sample and began to crush it. The force and displacement were recorded in real-time via a computer. The maximum force at which each sample failed, F, was recorded from the graphs and the tensile crushing strength, σ, was calculated using:

$$\sigma = \frac{2F}{\pi D h} \qquad (2)$$

where D and h are the diameter and height of the sample, respectively [40].

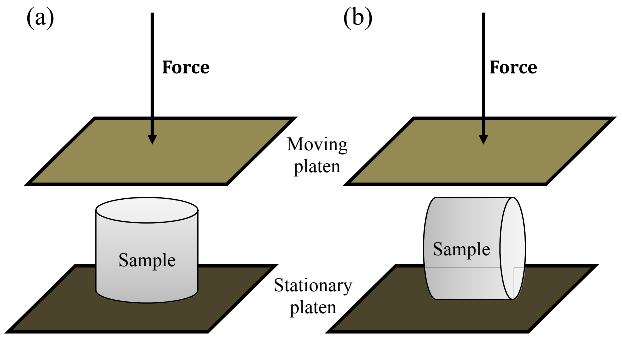

Fig. 1 – Orientation of crushing experimental setup during (a) compressive and (b) tensile strength testing.

2.4.2. *Impact resistance*

The impact resistance, also known as the shattering resistance or drop resistance, is designed to simulate the forces encountered during emptying and dumping of the densified products. Different variations of the impact resistance test have been used by various researchers. Several authors have dropped the densified samples from 1.85 m onto a metal surface four times and recorded the weight retained [41,42]. Ten repeated drops from a height of 1 m onto a concrete surface have also been used [43]. As advised by Richards [39], in this study, each briquette was repeatedly dropped from the height of 2 m onto a concrete surface until it fractured. The data were recorded and used to calculate the impact resistance index (IRI) using the following equation:

$$\mathrm{IRI} = \frac{100 \cdot n_d}{n_p} \qquad (3)$$

where n_d is defined as the number of drops of the sample, and n_p is the number of pieces the sample breaks into [39].

2.4.3. *Immersion tests*

Exposure to water in the form of rain or high humidity conditions can also adversely affect the quality of the densified product. Hence immersion tests were performed to assess the effects resulting from exposure to water. As advised by Richards [39], the water resistance was defined as 100 minus the percentage of water absorbed by the densified product after it has been immersed in water at room temperature for 1800 s (30 min), removed, wiped clean of surface water, and weighed.

3. Results and discussion

3.1. *Characterization*

The composition of the PKSB was determined using XRF spectroscopy and CHNS elemental analysis. Note that the XRF data are relative (sum to 100%) while the CHNS analysis provides absolute values (water free basis). Ash content was determined at 3% using thermogravimetric analysis. As evident from Table 1, there is an abundance of carbon in the

Table 1 – Element mass fraction of the PKSB using XRF spectroscopy and CHNS elemental analysis.

Constituent	%
XRF (relative)	
Mg	2.7
Al	1.2
Si	17.7
P	2.7
S	1.6
K	29.8
Ca	41.4
Fe	2.6
Others	<1
CHNS (absolute)	
C	81.4
H	1.6
N	1.8
S	0.16

PKSB. In addition, the extremely low ash content of the feedstock is of great interest for fuel purposes. The large carbon content is indicative of the favourable calorific value of the solid. The carbon content of raw PKS (prior to any sort of thermal treatment and charring) has been reported at 49.5–54.7% [22]. So it can be concluded that the thermal treatment used by the Hong Kong based company prior to expunging the PKSB residue from the gasifier has significantly made the biomass carbon-rich. If the oxygen to carbon ratio of a fuel is high, it will result in an unwanted over-oxidation in gasifiers leading to thermodynamic losses [44].

The higher heating value (HHV, also known as the gross calorific value or gross heating value) is determined by considering the cooling of reaction products to pre-combustion temperatures. Effectively, this means the latent heat of liquids (in particular water) is included in the HHV. The HHV is calculated with water exiting the system in liquid form, while the LHV is calculated with the assumption that the water product leaves as vapour. Various predictive equations have been developed for estimating the heating value of solid fuels from their elemental composition. Here, two such equations are used to estimate the HHV of the PKSB (using a conversion of 1 Btu/lb = $429.923\ \mathrm{MJ\cdot kg^{-1}}$):

Mason and Gandhi [45]

$$\mathrm{HHV}\left[\mathrm{MJ\cdot kg^{-1}}\right] = (0.461\times \mathrm{C}) + (1.443\times \mathrm{H}) + (0.188\times \mathrm{S}) + (0.105\times \mathrm{Ash}) - 11.986 \tag{4}$$

Mesroghli et al. [46]

$$\mathrm{HHV}\left[\mathrm{MJ\cdot kg^{-1}}\right] = (0.605\times \mathrm{C}) + (1.352\times \mathrm{H}) + (0.84\times \mathrm{N}) + (0.321\times \mathrm{S}) + (0.275\times \mathrm{Ash}) - 26.29 \tag{5}$$

where C, H, N, S, and Ash are the water free weight percentage of the carbon, hydrogen, nitrogen, sulphur and ash present in the solid fuel, respectively. Using Equations (4) and (5), the HHV of the PKSB is estimated at $28.18\ \mathrm{MJ\cdot kg^{-1}}$ and $27.51\ \mathrm{MJ\cdot kg^{-1}}$, respectively. Thus the gross calorific value of the PKSB is markedly higher than (and in some cases more than double) that of typical biomass and is on par with bituminous coal and lignite samples [47]. Hence the PKSB is potentially a very favourable energy source.

3.2. Compaction without starch

The as-received PKSB was first compacted without any pretreatment or addition of water. Regardless of the applied compaction pressure (10–100 MPa) or holding time (1–60 s), the resulting briquettes were so weak that they could not be ejected from the equipment after formation. Any attempt to eject the samples out of the compaction cell resulted in their disintegration into powders and numerous small fragments. Hence compaction of the as-received PKSB without addition of water was not possible. These results are in good agreement with those reported by Chin et al. [48] who produced biomass briquettes by pressing dried pulverized materials without any binder or water, resulting in PKS briquettes which did not show good resistance in water immersion tests and did not have satisfactory durability.

3.2.1. *Effect of water content*

An appropriate moisture content prior to densification has been shown to positively affect the mechanical strength of the final product [49]. The effect of water addition to the biomass samples can be three-fold: firstly, the existence of water promotes solid bridge formation. Secondly, van der Waal's forces are promoted. Thirdly, the presence of water has been shown to decrease the glass transition temperature of biomass constituents such as lignin, starch and gluten [50].

The compression of PKSB with various water contents (without the use of starch) was tested. Fig. 2 shows the measured tensile crushing strength of the samples prepared with different amounts of water. All the samples were compacted to 80 MPa and held for 10 s. As previously mentioned, when no water was used, the compacted sample was not durable and completely crumbled during ejection. An increase in water content initially leads to higher briquette strength. However, if the water content is too high, the briquettes fail to form correctly. The samples prepared with more than 40 wt% water were semi-solid and broke easily during handling before their strength could be measured.

3.2.2. *Effect of compaction pressure*

Initially, when pressure is applied during compaction, it will lead to some non-permanent elastic deformation of the sample that lasts only as long as the force is applied. As the pressure increases, permanent plastic deformation begins to occur [51]. Bonding arising from the diffusion of molecules from one particle to the next and the formation of solid bridges is more probable under higher pressures. Hence high pressures (and temperatures) cause better connection at the points of contact resulting in more dense and durable products [49,52]. In addition, higher pressures are known to decrease sample porosity. The relationship between pores and compaction strength has been studied and modelled [53,54]. Here, the PKSB samples were compacted to different pressures followed by subsequent tensile crushing strength testing. Fig. 3 shows the tensile crushing strength for samples prepared at different compaction pressures.

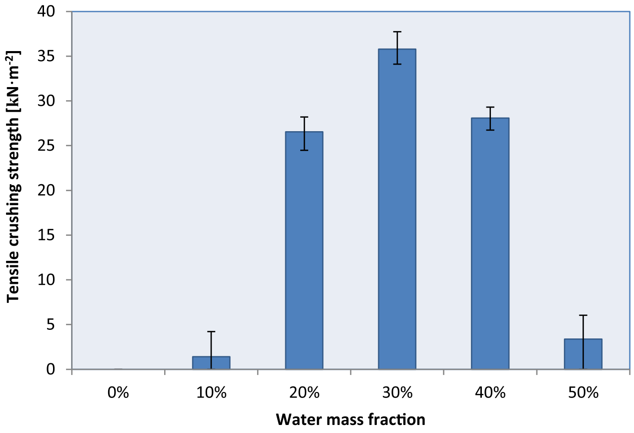

Fig. 2 – Tensile crushing strength of PKSB briquettes prepared with different water mass fractions. The applied compaction pressure of 80 MPa was held for 10 s.

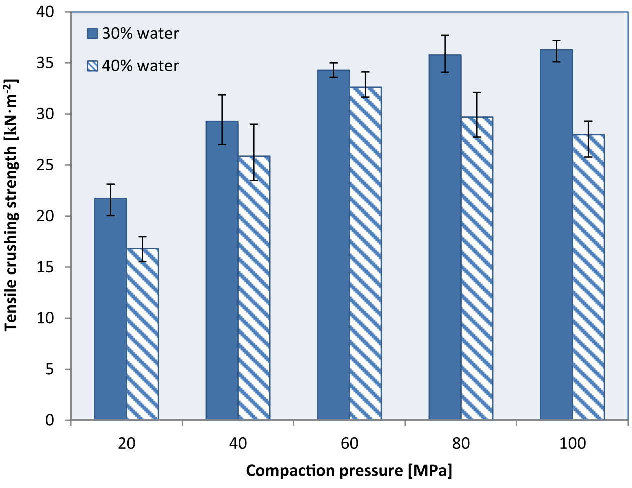

Fig. 3 — Effect of the compaction pressure on the tensile crushing strength of PKSB briquettes (compaction pressure held for 10 s; the mass fraction of water in the samples was 30 and 40%).

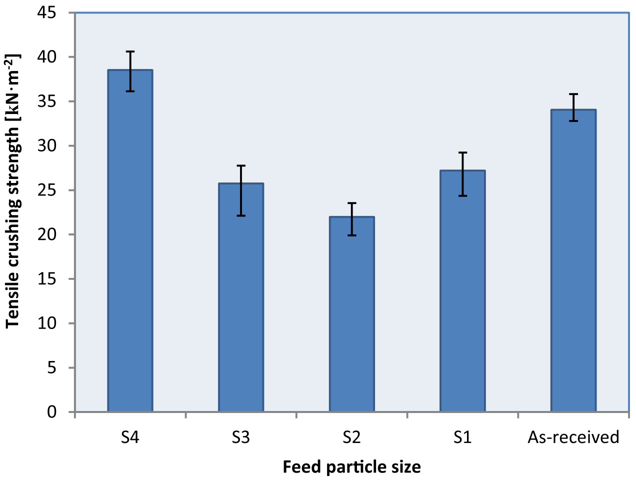

Fig. 4 — Effect of particle size on the compressive strength of the PKSB briquettes (30% water mass fraction) prepared at 80 MPa with 10 s holding time. Size categories: S1 > 3000 μm, 3000 μm > S2 > 700 μm, 700μm > S3 > 300 μm, and S4 < 300 μm.

For the 30% water sample, the tensile crushing strength increases with increasing compaction pressure and approaches a plateau above 60 MPa. For the 40% water content samples, the tensile crushing strength initially increases with increasing compaction pressure. A subsequent decrease in strength for compaction pressures above 60 MPa is then observed, which is in agreement with the work of Yaman et al. [55] who also found an optimum briquetting pressure above which unwanted fractures appeared in the product; they attributed the decrease in strength at higher pressures with "sudden dilation" of the briquette above the optimum pressure.

The results shown in Fig. 3 can be explained as follows: before compaction, when the water comes into contact with the PKSB, it penetrates into the porous structure of the particles as well as covering their surfaces and filling the void spaces between the particles. When pressure is applied to the PKSB during compaction, the inter-particle voidage decreases as the particles rearrange within the compaction cell. If an inter-particle void is completely filled with water, decreasing its volume will result in movement of the water. Specific surface area and pore volume measurements (not shown here) suggest that the porosity of the samples does not change on the nanoscale. In other words, the increase of compaction pressure does not lead to a decrease in the volume of the voids within the particle, i.e. the intra-particle porosity remains the same. Hence, as shown in Table 2, the apparent density of the PKSB briquette increases with increasing compaction pressure while the true density of the PKSB remains constant. The apparent density follows a linear trend with the logarithm of applied pressure, which is a common result in powder compaction studies [56]. When 100 MPa of pressure is applied, the apparent density of the PKSB increases more than 2 fold compared to its as-received state. At a given compaction pressure, the amount of water forced out of the inter-particle voids may inundate the particles leading to a decrease in the strength of the final product. However, if the initial water content of the sample is not higher than a given threshold (here 30%), the volume of water released will not lead to inundation and hence will not decrease the mechanical strength of the product.

3.2.3. *Effect of particle size and holding time*

In order to examine the effect of particle size on the PKSB briquettes, the as-received PKSB were crushed using the strain frame to powders followed by sieving. Three mesh sizes were used, namely 3000 μm, 700 μm, and 300 μm. The samples were separated into the following size categories: S1 > 3000 μm, 3000 μm > S2 > 700 μm, 700 μm > S3 > 300 μm, and S4 < 300 μm. When finer particles were used, the surface of the compacted briquette was visibly smoother without any cracks or coarseness. Fig. 4 shows the tensile crushing strength of the samples, prepared with a water content of 30% and compaction pressure of 80 MPa held for 10 s. The increase of feed particle size above 300 μm results in a decrease in tensile

Table 2 — The effect of compaction pressure on PKSB briquette density and porosity.

	Compaction pressure			
	None (as-received)	20 MPa	60 MPa	100 MPa
Apparent density [kg·m^{-3}], ρ_a	288 ± 35	590 ± 27	701 ± 36	747 ± 31
True density [kg·m^{-3}], ρ_t	2042 ± 15	2034 ± 10	2040 ± 10	2040 ± 9
Briquette porosity, ε calculated from Equation (1)	0.84–0.88	0.70–0.72	0.64–0.68	0.62–0.65

crushing strength. Previous studies have indicated that the strength of the densified product is generally inversely proportional to the feed particle size [54]. Smaller particles have greater surface area per unit volume and higher number of contact points during compaction; however if the particles are too small, they may lead to jamming within the equipment and adversely affect the production line. The as-received material (without any grinding or size segregation) is a mixture of particles with various sizes, and exhibits an acceptable tensile strength. The as-received feed enjoys the benefit of having both larger particles that aid in mechanical interlocking, and finer powders which increase the number of contact points. Thus, for practical purposes, there is no need to incur the additional step of grinding prior to densification.

In order to examine the effect of holding time on the tensile crushing strength of the briquette, the PKSB (30% water) was subjected to 80 MPa with various holding times. The holding time did not appear to affect the strength (data not shown). This is in agreement with findings of previous studies which have concluded that the holding time, also known as the retention or dwell time, has a significant effect only at lower compaction pressures [49]. Increasing of the holding time at 80 MPa did not appear to compact the samples any further and hence did not affect the tensile crushing strength of the final product significantly.

3.3. *Compaction with starch binder*

3.3.1. *Effect of curing time*

After a briquette is formed, the time at which its strength is measured is an important parameter. Usually the ‘green strength’, which is the strength measured immediately after densification is different from the ‘cured strength’ that is reported after the densified product has been stored for a duration of time. It is important to know if the densified product can remain strong even after it has been stored. Hence the time of strength measurement is essential when experimental values are being reported [1].

The strength of the briquette is dependent on cohesion forces, which can be divided into ‘true’ and ‘apparent’ cohesion. Apparent cohesion is the force that keeps particles agglomerated by capillary forces and mechanical interlocking of rough particle surfaces. The apparent cohesion forces allow for deformation and agglomeration of the particles but are mostly lost upon drying. The true cohesion forces are those that keep the particles together even after drying. These include electromagnetic and electrostatic forces of particles and cementing agents [51]. Since the compaction of the PKSB without binder resulted in briquettes with strength much lower than the benchmark target proposed by Richards, the use of a binder is necessary.

Fig. 5 compares the strength of briquettes produced with and without the starch binder. Note that the vertical axis is logarithmic, showing that the addition of starch increases the tensile crushing strength more than 100 fold after one day (86,400 s) or more of curing. Dried starch-bound samples exhibit a tensile crushing strength of 821 ± 26 kN m^{-2}, which is more than double the desired value of 375 kN m^{-2} proposed by Richards [39]. It is evident that adding the starch binder not only increases the strength of the products at any given curing time, but also results in a product that retains its strength after storage (true cohesion). Interestingly, the starch-bound samples become markedly stronger as the water within them evaporates. Starch-bound briquettes show no sign of strength loss even after two weeks of storage at ambient temperature and 30–50% relative humidity. It is speculated that as the water within the briquette evaporates, the starch can form a better ‘cement’ creating better consolidation. Thus as the water leaves the sample, the strength noticeably increases. Conversely, in the samples without the starch binder, the strength of the PKSB briquettes decreases by over a quarter of the green value after only one day of storage. It can be concluded that the compaction with water only has resulted in apparent cohesion of the particles; it is the capillary forces and liquid bridges of the water that keep the sample consolidated. Thus as the water evaporates, the samples visibly weaken. Hence in order to obtain true cohesion of the PKSB particles, the addition of a starch binder is imperative.

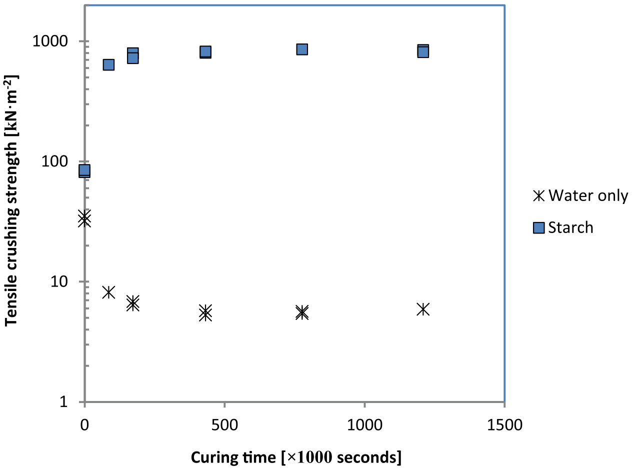

Fig. 5 – Comparison of PKSB briquette strengths at various curing times formed with and without starch binder. Note that the vertical axis is logarithmic.

3.3.2. *Quality testing*

Aside from the tensile crushing strength, the impact resistance of the samples was also tested. In the impact resistance testing, the samples did not break into sizeable fragments. Nonetheless, with the repetition of drops, small pieces gradually chipped off. For example, after the first 3 drops, less than 5% of the sample was chipped off in the form of dust and small pieces. After 10 drops, the total amount of chipped pieces neared 10% of the briquette mass, and the IRI was calculated at 167. Again, this value is considerably higher than the target IRI of 50 [39].

Finally, the water resistance of the briquettes was also tested. Immediately after immersion, bubbles started to emerge out of the briquettes and fine black powders were released into the water. The bubbling was accompanied by a slight fizzing sound. The release of fine black powders made the water opaque. After several minutes, the briquettes could no longer be seen. After 30 min, the blackened water was poured out of the container and the briquettes were recovered. Although the bulk of the briquette stayed intact, the release of black powder during the test resulted in the partial fragmentation of the samples. Overall, the immersion tests showed water resistance values lower than 50%. Hence for practical applications, the briquettes should not be subjected to wet conditions, for example left uncovered in the rain.

4. Conclusion

Compacted briquettes obtained from palm kernel shell biochars (PKSB) were formed and tested. The PKSB briquettes exhibit excellent potential as solid fuel due to their high calorific value, low ash content, and high tensile crushing strength. The optimum water content for maximum tensile crushing strength was found to be 30%. The strength of the briquettes increased if PKSB particles were ground to particles smaller than 300 μm. Nonetheless, briquettes formed from the as-received material without size segregation also exhibited comparable tensile crushing strengths. The larger particles in the as-received PKSB are thought to improve mechanical interlocking while the finer particles increase the number of contact points during compaction. When only water was used, the compaction holding time did not affect the tensile crushing strength of the product significantly. The use of 10% starch resulted in a 100-fold increase of the tensile crushing strengths of the briquettes, which persisted even after weeks of storage. It is speculated that the evaporation of water helped the starch act as a better cementing agent. Hence using starch as a binder led to 'true' cohesion of the particles (as opposed to the 'apparent' cohesion when only water was used). It is advised that the densified product should be stored sheltered from water to avoid disintegration.

Successful densification of biomass can allow gasification companies to make further utilization of the solid residues ejected from gasifiers. Not only does compaction more than double the apparent density of the PKSB, but due to the uniform shape and size of the briquettes, they can more easily be handled and used in standard combustion equipment.

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